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REVIEW

Are ecosystem services adequately quantified?

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Summary

1. Quantification of ecosystem services (ES) is an important step in operationalizing the concept for management and decision-making. With the exponential increase in ES research, ES have become a 'catch-all phrase', which some suggest has led to a poorly defined, impractical and ambiguous concept. An overview of the methods used in ES quantification is needed to examine their scientific rigour and provide guidelines for selecting appropriate measures.

2. We present a systematic review of 405 peer-reviewed ES research papers to address the question: 'Is the biophysical and socio-economic reality of ES adequately quantified? First, we considered whether ES measures are scientifically rigorous enough by considering four predefined criteria (the type of data used, quantification of uncertainty, validation done and data reported). Secondly, using a novel approach, we determined which part of the ES cascade was measured: the ecosystem property, function, service, benefit or value.

3. Our results showed that each of the 21 ES analysed had on average 24 different measures, which may indicate the complex reality of ES and/or suggest a potential lack of consensus on what constitutes an ES. We found that uncertainty is often not included and validation mostly missing.

4. When analysing which part(s) of the ES cascade each measure corresponded to, we found that for regulating ES, ecosystem properties and functions (ecological aspects) are more commonly quantified (67% of measures). Conversely for provisioning ES, benefits and values (socio-economic aspects) are more commonly quantified (68%). Cultural ES are predominantly quantified using scores (35%).

5. In conclusion, ES appear to be poorly quantified in many cases, as often only one side of the cascade is considered (either the ecological or socio-economic side) and oversimplified and variable indicators are often used.

6. *Policy implications*. This review provides a detailed overview of ecosystem services (ES) quantification (ranging from simple scores to advanced methods) with the aim to support future ES quantification and ultimately the successful application of the ES concept.

Key-words: actual/potential ecosystem services, ecosystem service cascade, indicators, interactions quantified, operationalization, stakeholder engagement, uncertainty quantified

Introduction

Ecosystem services (ES) are widely defined as 'the benefits that humans derive from nature' (MEA 2005, TEEB 2010) and are seen as the link between biophysical reality (ecological system) and human well-being (socio-economic system) (Haines-Young & Potschin 2010; TEEB 2010). The ES cascade, originally developed by Haines-Young & Potschin (2010), provides a useful conceptual framework for operationalizing this by breaking the concept up into measurable entities. In the most commonly used ES cascade, ecosystem properties (biophysical structure or stock) produce ecosystem functions (flows), which provide ES that have benefits for humans, to which a value (economic) can be attributed (Potschin & Haines-Young 2011). This currently accepted ES cascade with its five

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parts has been widely adapted by many other researchers in varying degrees of complexity (e.g. van Oudenhoven *et al.* 2012; Hernández-Morcillo, Plieninger & Bieling 2013). Saarikoski *et al.* (2015) offer perhaps the most complicated ES cascade, dividing it into seven distinct entities by splitting ES into 'final' and 'intermediate' ES, and benefits into 'benefits' and 'human well-being'. On the other hand, Luederitz *et al.* (2015), when operationalizing the ES cascade, found ES and benefits to be synonymous. Whichever ES cascade is used, it is widely agreed that a full analysis of each ES requires that both the ecological and socio-economic aspects need to be considered, as well as the relationship between them (de Groot *et al.* 2010; Haines-Young & Potschin 2010).

The broad definition of ES has resulted in it becoming a 'catch-all phrase', which some suggest has resulted in a poorly defined, impractical and ambiguous concept (Seppelt *et al.* 2011; Nahlik *et al.* 2012). However, some consider that this same ambiguity promotes transdisciplinary research and encourages creativity (Schröter *et al.* 2014). Certainly, there are diverse methods used to measure ES, ranging from simple scoring systems or rapid assessments to complex field-specific measurements. As ES are difficult to measure, indicators are often used as a proxy (Layke *et al.* 2012; Kandziora, Burkhard & Müller 2013). Some have noted that this high diversity of measures used for each ES results in a lack of consistency and that many of these measures do not often succeed in quantifying the ES itself (Saarikoski *et al.* 2015). A full quantification of an ES is difficult as multiple aspects of the ES cascade require inclusion and it is therefore not possible to have a single measure per ES (van Oudenhoven *et al.* 2012; Kandziora, Burkhard & Müller 2013). Some studies have addressed this by providing separate indicators for each part of the cascade with the aim to contribute towards a better quantification of ES (van Oudenhoven *et al.* 2012; Hernández-Morcillo, Plieninger & Bieling 2013; Kandziora, Burkhard & Müller 2013; Luederitz *et al.* 2015; Saarikoski *et al.* 2015).

There are also concerns about the scientific rigour of ES research which might be linked to the poor understanding and operationalization of the ES concept (Seppelt *et al.* 2011; Nahlik *et al.* 2012; Van der Biest *et al.* 2015). Common flaws include the confusion between the quantification of stocks and fluxes, for example measuring carbon stocks instead of carbon sequestration for the ES Climate Regulation (Boyd & Banzhaf 2007), or the use of oversimplified proxies (Eigenbrod *et al.* 2010). Other problems are related to the type of data used in ES studies, which may not always be appropriate for the specific research question (e.g. data from global-scale data bases, coarse mapping or data from the literature) or scale (de Groot *et al.* 2010; Pinto *et al.* 2010; Busch *et al.* 2012). Additionally, many studies do not distinguish between the potential and the actual supply of ES by an ecosystem (Van der Biest *et al.* 2014). In many cases, maps, models and remote-sensing analyses are not validated, and in many studies, there is no indication of uncertainty (Seppelt *et al.* 2011). In studies measuring more than one ES, interactions (trade-offs/synergies) among these ES are often not considered (Pinto *et al.* 2010; Seppelt *et al.* 2011; Smith *et al.* 2013).

When it comes to implications for policy and real-world application, stakeholder involvement is crucial, but often lacking in ES research (Seppelt *et al.* 2011). Quality of ES studies depends to a large extent on constraints such as time, money and data availability (Busch *et al.* 2012; de Groot *et al.* 2012; Layke *et al.* 2012), and in cases where these are limiting, scientific quality is frequently compromised (de Groot *et al.* 2010). To help operationalize the ES concept and to ensure high-quality research in future, there is a need for an overview of the measures and indicators currently used in the field of ES with the long-term vision of screening and selecting measures that are appropriate and red-flagging those that are not. To address this, we conduct a systematic review of the ES literature to examine the measures currently used to quantify ES. The central research question of this review is: 'Are current methods adequately quantifying the biophysical and socio-economic reality of ES?' We address this question using two methods (i) by assessing the scientific rigour of each measure and (ii) by assessing which parts of the ES cascade are being quantified for each ES.

Materials and methods

Based on 19 key reviews and meta-analyses of ES measures and indicators, we selected 21 commonly quantified ES (Table 1) from three ES categories using the typology from the TEEB (TEEB 2010) and CICES lists at the group level (Haines-Young & Potschin 2013). We selected three ES categories, excluding supporting ES to avoid double counting (Haines-Young & Potschin 2013). Therefore 'nutrient cycling', 'biodiversity' and 'habitat' were not included as ES in this review. We performed a systematic literature search in Elsevier's Science Direct data base in April 2014 and included all the literature until that date. The aim was to capture the literature at the core of the field of ES, and therefore, specialized research that only alluded to the ES concept was beyond the scope of this study. Search terms included 'ecosystem service' and '[the name of the ES]' (e.g. 'climate regulation') in abstracts, titles and keywords. Where appropriate, additional search terms for certain ES were used to accommodate the variations in nomenclature (e.g. 'carbon' for Climate Regulation) (Table 1). We identified 553 English-language peer-reviewed papers that were divided and read by the lead researchers (A.J.R., A.B., M.B.). We excluded grey literature and books as this would build in a bias towards reports written in languages mastered by the authors. Any papers not explicitly measuring ES were excluded, resulting in a final number of 405 papers that were reviewed and captured in a data base.

For each paper, all studied ES were identified and key information was recorded, including paper descriptors (e.g. citation, year and journal), the ecosystem, scale (local, regional, national, continental and global) and geographical information (location, country and continent). The state of the ecosystem was noted if it was possible to discern from the paper whether the sites were pristine,

Table 1. List of ecosystem services (ES) and corresponding search terms used in the literature review. Each search term was combined individually with the term 'ecosystem service' to capture the literature at the core of the field of ES

	Ecosystem service	Search terms
Provisioning		
1	Food Production	Food; nutrition; fish
2	Water Provision	Water; drinking; irrigation
3	Materials & Fibre	Material; fibre; timber; raw material; wood
4	Energy & Fuel	Energy; biomass; fuel
5	Genetic Resources	Genetic
6	Medicinal Resources	Medicine/medicinal
7	Ornamental Resources	Ornamental
Regulating		
8	Water Purification	Water purification; water waste treatment; water nutrient; water quality
9	Water Regulation	Water regulation; water flow; water quantity; flood prevention/attenuation; drought mitigation/prevention; storm protection; water retention
10	Air Quality Regulation	Air quality; fine dust (capture); air pollutants; dry deposition
11	Soil Quality Regulation	Soil quality; soil formation; soil fertility; nutrient cycling (soil nutrients); weathering; recycling; microbial processes; decomposition
12	Soil Retention	Soil retention; erosion; sedimentation (soil conservation)
13	Climate Regulation	Climate; carbon; sequestration; gas
14	Pollination	Pollination
15	Life Cycle Maintenance	Life cycle maintenance; nursery /nurseries
16	Biological Control	Biological control; pest
Cultural		
17	Recreation & Tourism	Recreation; tourism; entertainment; amenity
18	Scientific & Educational Services	Science; scientific; education; cognitive development
19	Heritage, Cultural, Bequest, Inspiration & Art	Heritage; cultural; bequest; inspiration; art
20	Aesthetic Services	Aesthetic; well-being
21	Symbolic, Sacred, Spiritual & Religious Services	Symbolic; sacred; spiritual; religion

degraded, restored or a combination of these. Lastly, it was noted whether economic valuation was performed. For each ES, all measures presented in each paper were identified. The name of each measure, the method and the units were recorded. Many papers considered more than one ES and many ES had more than one measure per paper. Therefore, we have many more entries than the total number of papers (n = 1625 measures). All measures found per ES were summarized in a table (see Appendix S1 in Supporting Information). Additional data included whether the actual or potential ES was measured, whether the interaction effects between ES were considered (only if more than one ES is considered in one paper) and whether scenarios were investigated. We also looked at potential societal impact by checking whether recommendations for policy makers or managers were included and whether stakeholders were involved in the project.

To determine whether the biophysical and socio-economic reality of ES is adequately quantified, we used two key criteria. First, we considered whether the measures were scientifically rigorous by looking at whether uncertainty was calculated, whether the validation was done (when relevant, e.g. mapping, modelling and remote-sensing studies) and what types of data were used. We included eight categories of 'data types': four 'active' methods (i.e. those that generate primary data, such as field measurements, mapping, modelling and remote sensing), three 'passive' methods (e.g. theoretical studies, data from data bases or literature) and additionally expert judgement. We also considered whether biophysical/monetary data are available in the paper as opposed to scores or theoretical studies. Secondly, we looked at which parts of the ES cascade were quantified by each measure. We use the ES cascade structure of van Oudenhoven *et al.* (2012)/TEEB 2010, because they separate ecosystem properties from functions and do not confuse 'processes' and 'functions'. We defined the five categories according to the definitions taken from these widely accepted sources. Ecosystem properties (EP) are defined as the biophysical structure of an ecosystem, whereas ecosystem functions (EF) or processes are 'any change or reaction that occurs in an ecosystem (biophysical, chemical or biological)' (TEEB 2010). 'Ecosystem services' (ES) are defined as the 'contributions of ecosystems to human well-being' (TEEB 2010), whereas 'benefits' (B) are 'positive changes in well-being from the fulfilment of needs and wants' (TEEB 2010). Lastly, 'value' (V) is defined as the 'economic worth of the change in well-being'. Measures were assigned to each part of the ES cascade according to these definitions and the consistency was controlled by internal cross-checking to minimize misclassifications. Since not all measures fit into the five parts of the cascade, we included two additional categories that are considered not to be part of the cascade: 'score' for all studies using scores either from social surveys, biophysical assessments or expert judgement, and 'other' for measures that did not fit into any of these categories (e.g. disservices). Although scores could be mapped onto the ES cascade, we chose not to do so as we deemed that separating scores from the cascade provides more useful information on the types of measures used. Some researchers considered more than one aspect of the ES cascade and each of these was recorded and these papers were noted.

Results and discussion

GENERAL OVERVIEW OF ES RESEARCH

The number of papers published in the field of ES science has been exponentially increasing since 2005 with about 90% of the research taking place from 2009 onwards (365 out of 405 papers in our review). These 405 papers are from a total of 74 journals, with three journals dominating (27%): Ecological Indicators, Ecological Economics and Agriculture, Ecosystems and Environment, respectively. The most studied ES are mainly regulating services (48%) and the least studied ES are mainly provisioning (26%) and cultural ES (26%). Most papers studied only one or two ES (59%), only 25% investigated more than three and only one considered all 21 analysed in this review. From 2007 onwards, there appears to be a slight increasing trend in the number of papers studying more than three ES together. ES studies have been conducted in many countries world-wide (83 countries in total). A disproportionate number of studies (40%) have been done in only five countries: the USA, China, UK, Australia and Germany (Fig. 1). This might be an artefact of population or country size, human development index, or of reviewing only English-language journals. The majority of studies are carried out at a local or regional scale (81%) and mostly in agriculture, forest, grassland and human settlements (e.g. built-up land, mines) (84%). Nevertheless, very few studies (20%) explicitly consider the state of the site (e.g. degraded, pristine or restored) or make a comparison between different states (13%). All ecosystems appear to be equally well studied on each continent.

APPLICATION OF ES CONCEPT

There are several key issues that all studies should take into consideration to make them applicable for use in practice. First, it is important to distinguish between potential, actual and sustainable supply and demand for ES and to be consistent and transparent about this. Half of all studies measured potential ES, which can be problematic because this might not always reflect what an ecosystem actually supplies or sustainably could supply, or what is actually or sustainably used by society. Only 3% of studies considered both actual and potential ES, which could give more clear information about the sustainability of ES delivery in those cases. Secondly, and similar to other studies (Pinto *et al.* 2010; Seppelt *et al.* 2011; Smith *et al.* 2013), we found that only 26% of studies considering more than one ES investigate the relationships between those ES. Therefore, most studies are considering ES in isolation and neglect the underlying complex interaction effects. These might have significant impacts and are especially critical to understand when doing an ES assessment for decision-making purposes. Thirdly, it appears that few studies considered scenarios (24%), and fourthly, even fewer considered stakeholder involvement (16%), as was also found by Seppelt *et al.* (2011) (Table 2). Lastly, we found that 60% of studies gave some form of recommendation for management or decision-making in varying degrees of detail. There is a slight increase in this over time; however given the application-based nature of the field, this should still be improved (Table 2).

ANALYSIS OF ES MEASURES

A very diverse set of measures was obtained for each of the 21 ES studied (range: 5–59). For example, Climate and Water Regulation both had 59 different measures, whereas Food Production, equally frequently studied, had only 23 (Table 2, Appendix S1). This high diversity of measures may either be an indication of the complexity of an ES (e.g. a well-studied ES with many components, such as Climate Regulation) or be an indication of a lack of consensus or understanding of how a particular ES should be measured (e.g. poorly studied ES such as Ornamental Resources). This high diversity of measures has consequences for the comparability of studies. To further determine whether the biophysical and socio-economic reality of ES is adequately quantified, we used two key criteria: first, whether the measures were scientifically rigorous and secondly which part of the ES cascade researchers measured.

Criterion 1: scientific rigour of ES measures

We found four major areas of concern in ES research which call the scientific rigour of the field as a whole into question. The first concern is that very few studies (23%) consider measures of uncertainty for their results, and although this is improving slightly with time, the proportion for the most recent years is still very low (Table 2). Secondly, there is also a high percentage of studies that do not report any kind of validation for mapping, modelling or remote-sensing exercises (33%). The third concern is that only a fifth of studies used actual field measurements, and only roughly half of all studies used active methods. Active methods are slightly more common for regulating ES (52%) and studies at a local and regional scale (55%). Studies using data from the literature and data bases make up about 41% of the total. Lastly, as many as 31% of studies do not report any data (e.g. display only ranges on a map, or data converted to scores), which is problematic for information transfer and quality control purposes. Overall, to gain more credibility as a field of science in its own right, there is a great need for more critical appraisal of ES research and greater efforts at quality control.

Criterion 2: cascade analysis

Overall, for all 21 ES, four of the parts of the ES cascade (properties, functions, benefits and values) are equally well quantified (Appendix S1). Interestingly, no measures have been developed for the 'ES' part of the cascade, when categorizing the measures according to the definitions outlined in the methods section. For provisioning ES, benefits and values are more commonly measured (60%) (Fig. 2). For regulating ES, properties and functions are the dominant measures (62%), whereas cultural ES are mainly quantified using scores (43%). Most measures were based on only one part of the ES cascade: properties

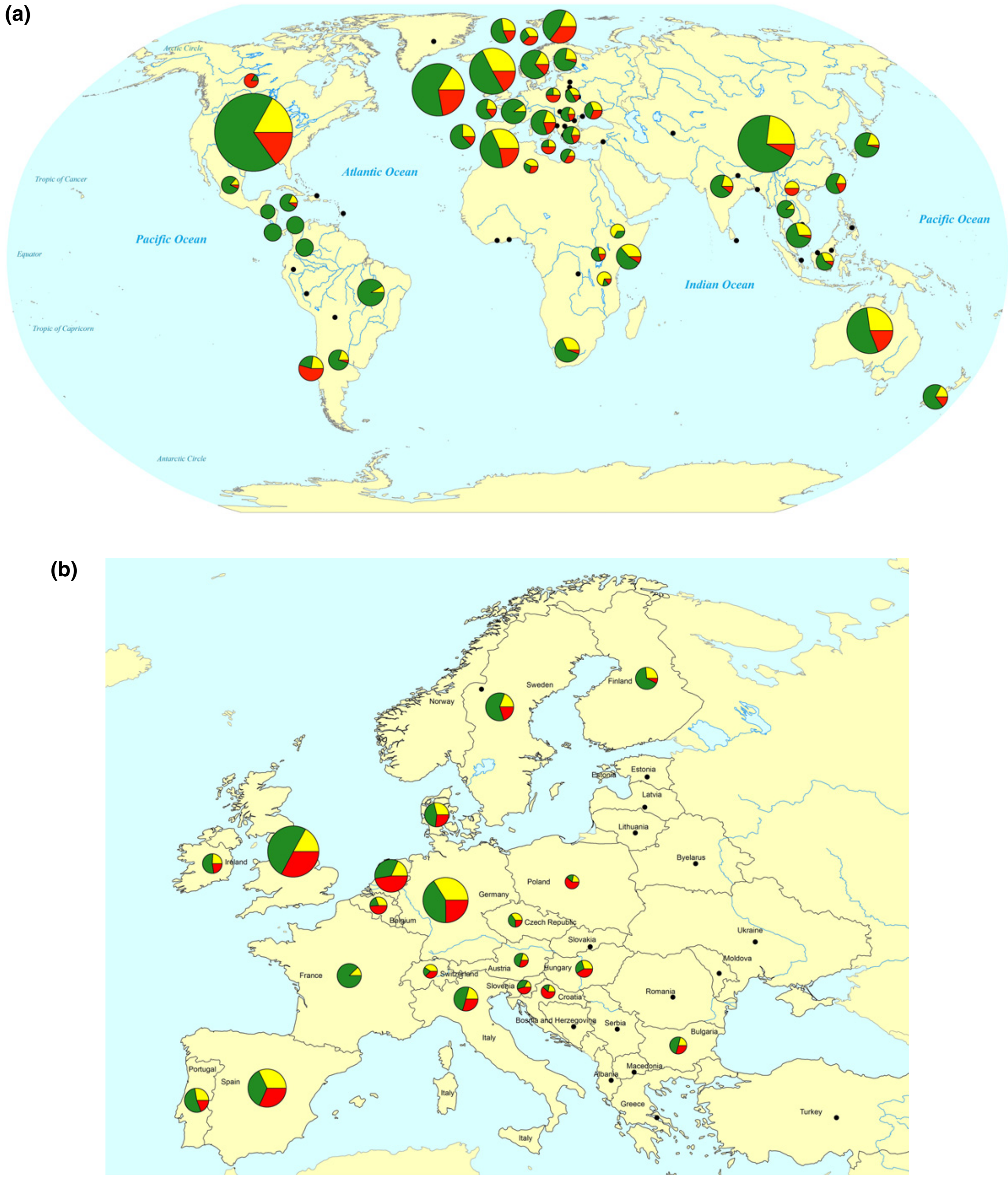

Fig. 1. The distribution of ecosystem services (ES) studies globally (a) and in Europe (b). All markings represent the 83 countries globally and the 35 countries in Europe, respectively, in which ES studies have been conducted. Pie charts show the relative proportion of ■ provisioning, ■ regulating and ■ cultural ES which have been studied, corrected by the number of ES in each category (seven provisioning, nine regulating and five cultural). Black circles (•) indicate countries where only one study has been done. The size of the pie charts is representative of the number of ES studies done in each country with, for (a) the greatest being 60 in the USA and the smallest two (e.g. Canada) and for (b) the greatest being 27 in the UK and the smallest two (e.g. Switzerland). [Colour figure can be viewed at wileyonlinelibrary.com].

(17·2%), functions (16·7%), benefits (8·6%) and values (16·4%). This differs from the findings of Luederitz *et al.* (2015) who found that more urban ES studies considered multiple parts of the ES cascade, thereby operationalizing the ES cascade more successfully. We found that the parts of the cascade most commonly studied together were benefits and values (8·4%), followed by functions and values (4·0%), properties and functions (3·5%) and functions and benefits (0·2%). Studying more than two parts of the ES cascade was very rare (0·7%). The remaining 20% of measures used scores, or other means to quantify ES.

PROPERTIES

The properties of an ecosystem are not directly related to the supply of an ES to society as this is determined by many

Table 2. Information about the applicability of the research and the scientific rigour of ecosystem service (ES) measures, per ES and the average overall. The percentage of studies and the number of measures give an indication of the diversity of measures for each ES. The applicability of the research was evaluated using two criteria: whether stakeholders were involved and recommendations made. Scientific rigour is evaluated using several criteria, including whether uncertainty is quantified, validation done where relevant (mapping, remote-sensing and modelling studies), whether active methods were employed (actual field measurements, mapping, modelling and remote sensing) and whether data were present in the paper for scrutiny. Each of the six criteria is expressed as a percentage of the total number of measures for each ES

Ecosystem service	Percentage of studies (%)	Diversity (No. of measures)	Stakeholder involvement (%)	Recommendation (%)	Uncertainty (%)	Validation (%)	Active methods (%)	Data present (%)
Food Production	10·1	23	15·7	67·4	20·8	33·3	38·1	68·0
Water Provision	5·9	27	20·3	69·6	30·4	13·9	43·1	73·4
Materials & Fibre	5·5	15	25·0	72·4	23·7	38·5	45·6	71·1
Energy & Fuel	2·4	13	8·5	66·0	12·8	33·3	40·2	55·3
Genetic Resources	1·0	8	18·8	56·3	25·0	0·0	40·0	81·3
Medicinal Resources	0·7	5	55·6	55·6	33·3	50·0	46·7	55·6
Ornamental Resources	0·3	5	60·0	40·0	0·0	-	33·3	80·0
Water Purification	8·5	49	11·8	58·8	27·9	43·2	50·0	71·3
Water Regulation	8·7	59	14·3	48·6	20·7	22·2	48·0	62·1
Air Quality Regulation	2·1	11	16·7	70·0	20·0	40·0	44·7	63·3
Soil Quality Regulation	9·0	42	2·6	43·2	22·6	75·0	64·5	79·5
Soil Retention	8·3	38	13·0	52·8	25·9	39·4	54·5	73·1
Climate Regulation	13·6	59	9·2	61·7	27·0	29·0	50·4	78·1
Pollination	3·6	24	8·7	71·7	30·4	28·6	53·2	73·9
Biological Control	2·5	19	15·6	65·6	21·9	25·0	51·3	68·8
Life Cycle Maintenance	0·7	6	12·5	75·0	37·5	100·0	27·3	75·0
Recreation & Tourism	7·9	16	19·0	61·3	13·1	28·2	45·7	61·3
Scientific & Educational Services	1·7	18	20·8	54·2	8·3	0·0	39·0	45·8
Heritage, Cultural, Bequest, Inspiration & Art	2·7	28	33·3	64·3	19·0	25·0	49·3	52·4
Aesthetic Services	3·3	27	25·5	56·9	17·6	30·0	42·0	52·9
Symbolic, Sacred, Spiritual & Religious Services	1·6	15	35·7	57·1	14·3	15·4	63·3	57·1
Average	4·8	24·1	15·5	59·7	22·9	32·8	48·3	69·1

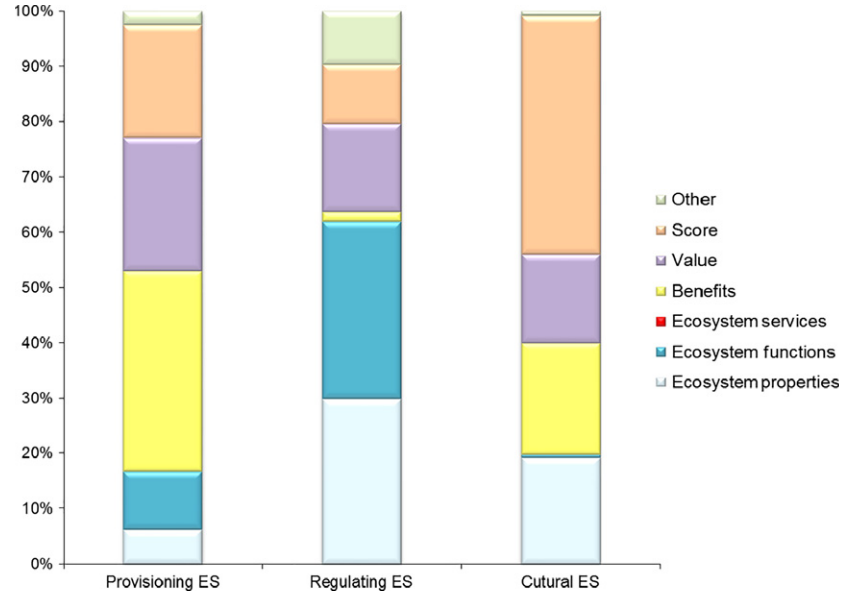

Fig. 2. The percentage of measures in each part of the cascade for the three ecosystem service (ES) categories, for all 21 ES. Where measures are from more than one part of the ES cascade, they are accounted for in each of these parts. [Colour figure can be viewed at wileyonlinelibrary.com].

other factors, such as environmental processes (both biotic and abiotic), infrastructure, sustainable yield and demand. The most frequently used measures for ecosystem properties are land use/land cover or habitat (%, ha), which is sometimes combined with additional information such as soil type, vegetation biomass and/or volume (Fig. 3,

Appendix S1). However, even adding these abiotic parameters to land-use/land-cover maps has been shown to yield little improvement in ES estimation (Van der Biest *et al.* 2015). Another common measure is the stock of various ecosystem properties, which is inappropriate as an ES measure as ecosystems are dynamic and stocks are constantly fluctuating. The most common example is that of using standing biomass as a measure of carbon sequestration for the ES Climate Regulation. For Water Purification, ecosystem properties such as total Nitrogen, total Phosphorus or turbidity are frequently measured instead of the contribution of the system to the regulation of water quality (i.e. what part of the change is a result of the ecosystem filtration mechanism). For all ES that depend on biodiversity, such as Genetic Resources, Biological Control, Pollination and Life Cycle Maintenance, simple measures or indicators of biodiversity and population size are often used. For example, Genetic Resources are estimated using species richness (Ford *et al.* 2012); however, the two are not necessarily directly related. Overall, the relationship between biodiversity and ES is poorly understood, and more research on this is needed so that indicators for these often less understood ES can be developed (Schröter *et al.* 2014; although see Gascon *et al.* 2015).

FUNCTIONS

Where measuring ecosystem properties alone is weak, measures of ecosystem functions are stronger as they give a better idea of ES supply and how this fluctuates spatiotemporally. The processes/functions underpinning each ES are diverse and comprise many different aspects (components) (Smith *et al.* 2013). The overview of measures for ecosystem functions is grouped into six categories. First, for water-related ES, measures for Water Provision include water yield, groundwater recharge and water flow rate (for details, see Fig. 3 and Appendix S1). Measures for Water Regulation are similar, but also include the regulation of these fluxes such as regulation of peak flows and low flows, and stormflow responsiveness. Water Purification is measured by the changes in nutrients spatially (e.g. differences between inlet/outlet), or decomposition rates. Secondly, for soil-related ES, measures include soil formation, conservation and erosion regulation (Soil Retention) and decomposition rate, biological respiration, soil formation and nutrient cycling (Soil Quality Regulation). Thirdly, there are three main types of measures for Climate Regulation, and these relate to carbon sequestration (above- or below-ground), greenhouse gas sequestration/emission and net primary productivity. Fourthly, Air Quality Regulation is usually quantified by estimating vegetation cleaning capacity either by dry deposition rate/velocity, or by pollution removal rate by plants. Fifthly, for ES related to biodiversity, measures include intraspecific diversity (Genetic Resources), pollination effectiveness and visitation rates (Pollination) and predation rate, plant growth rate and infestation rates (Biological Control). Lastly, only one measure relating to ecosystem functions was found for cultural ES, specifically the annual increase in tree leaf area (Aesthetic Services). We also found some isolated cases of misrepresentation, where authors claim to be measuring a function, but actually only measure a property (e.g. measuring carbon stocks instead of carbon sequestration).

ECOSYSTEM SERVICES

No measures were found for the ES part of the cascade.

BENEFITS

Benefits are most commonly measured for provisioning ES because they are tangible, and often have well-developed markets, both of which make them easier to quantify (Layke *et al.* 2012; Luederitz *et al.* 2015). Measures for benefits can be divided into two main groups: those related to societal demand (e.g. harvest of food or the number of species available for ornamental or medicinal use) and those linked to actual use, expressed, for example, per household (e.g. food consumed, actual water use or the number of visits). Some other measures for benefits include outputs, such as the number of publications, or the number of paintings/songs inspired by an ecosystem (refer to Appendix 1 for details). For regulating ES, only one example was found (quality and quantity of fruit supplied as benefit of Pollination). By definition, benefits also have many components, for example food provision, nutrition, health and the appreciation of food for the ES Food Production. Some would argue that ES are separate from benefits, and instead, they generate many different benefits (e.g. nutrition, enjoyment of food as benefits), while the ES would then be 'amount of food'. However, the very definition for ES contradicts this: 'the benefits/contributions humans derive from nature' (MEA 2005, TEEB 2010). Furthermore, having this extra step in the ES cascade seems redundant (e.g. the nutritional value of food (g kg^{-1} or Joules m^{-2}) is simply multiplying the weight of the food by a calorific value).

VALUE

Only one-fifth of ES studies performed a monetary valuation, which seems surprisingly low. For all ES, some form of monetary value is studied, but it is most frequently done for provisioning ES and Recreation & Tourism. Measures for the value of ES are confined to economic valuation methods, of which four main types appear. First, the most simple and rapid measure is the 'unit value per habitat type', which is often based on benefit transfer (€ ha^{-1} $year^{-1}$). Furthermore, many of these studies use the global values from Costanza *et al.* (1997), which are rough guidelines. For this approach, it is essential that the case study, from which values are taken, is comparable to the study in question. Secondly, many studies use the market price method. However, net value is a more

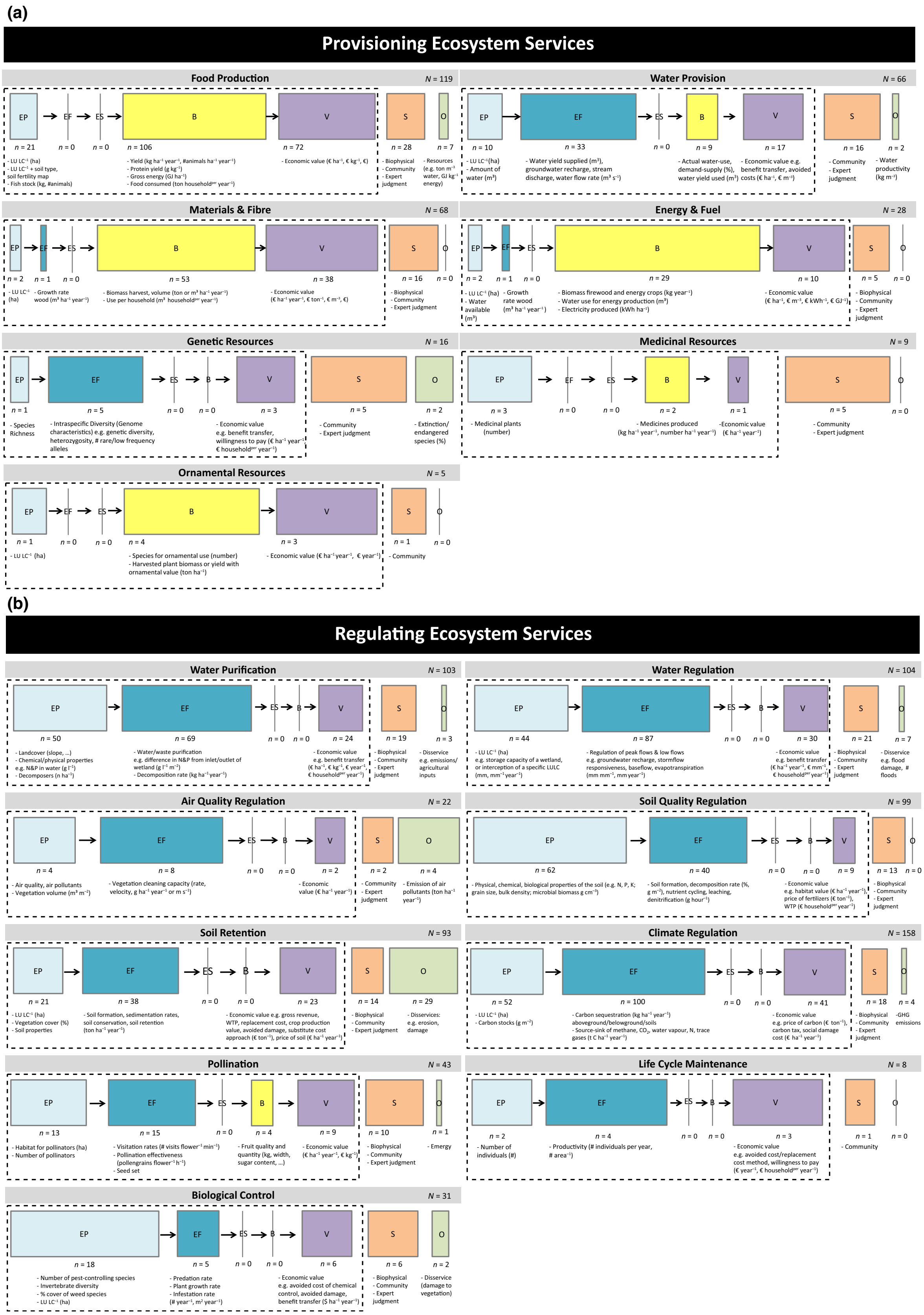

Fig. 3. The cascade analysis for (a) provisioning, (b) regulating and (c) cultural ecosystem services (ES). The bar graph in each diagram indicates which parts of the cascade are most commonly measured and the text beneath gives examples of the main types of measures used. The stippled line indicates the extent of the traditional cascade. EP: ecosystem properties, EF: ecosystem functions, ES: ecosystem services, B: benefits, V: value, S: score, O: other. 'N' refers to the number of papers, and 'n' refers to the number of measures. [Colour figure can be viewed at wileyonlinelibrary.com].

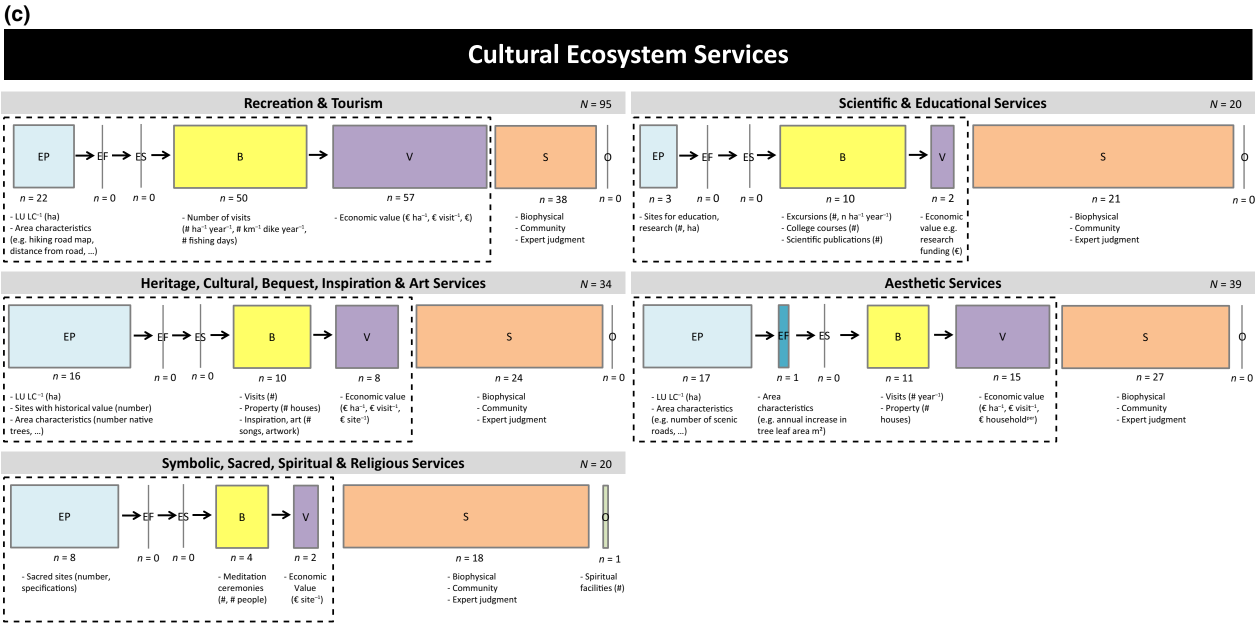

Fig. 3. (Continued).

appropriate method to determine the 'added value' of an ES. Net value is the market price corrected for production costs (€ ton^{-1}, € m^{-3}). In some other cases, the total value of a sector (e.g. fish sector, agricultural sector) for a specified area (€ ha^{-1}), or the research funds or budget (Scientific & Educational Service), is used. Thirdly, avoided cost or replacement cost is commonly used, such as avoiding flood damage (avoided cost), or avoiding the cost of a water treatment plant (replacement cost). Lastly, the 'willingness-to-pay' method (a stated preference method) is used (€ household^{-1}, € person^{-1}, € visit^{-1}). Monetary valuation of ES reflects the benefit to the society in monetary values. However, for many ES and particularly for regulating ES, the benefit is rarely estimated. Therefore, the monetary valuation of these ES is a value of the supply of ES. It is important to consider the difference between valuing the supply and the benefit, since the supply may give an overestimation of the economic value of an ES.

SCORES

Using simple indicators like scores can be an effective way to incorporate information from stakeholders into an ES assessment and can also be a valuable method to compare different ES and include ES for which no good measures exist. Scores often take the form of the 'perceived' importance of an ES ('non-economic valuation') and are derived from interviews with community members and local people or experts (scientists or practitioners from government or industry), or biophysical assessments. Biophysical scoring systems can either be simple, rapid assessments (qualitative categories, indicators) or more complex models. There are some limitations to using scores, such as their subjectivity, vagueness, oversimplification and sometimes lack of transparency. Depending on the purpose of the assessment, where more objectivity is needed, full ES quantification may be more appropriate. There are some ES for which few measures exist besides scores, such as Scientific & Educational Services and Symbolic, Sacred, Spiritual & Religious Services (Appendix S1). This suggests that these ES are poorly understood and that adequate measures are difficult to derive. There is a need for more research to understand what exactly these ES are, and whether they are important; if not, a rethinking of the list of ES may be required.

OTHER

There are a number of measures that do not fit into the five parts of the ES cascade, nor are they scores. This information is useful as extra information, but it is inappropriate when used as quantification of the ES. The most common measures of this type relate to ecosystem disservices, negative consequences of ecosystems to humans, such as emissions from ecosystems or number of floods. While ecosystem disservices are not related to the ES itself, they might in some cases shed light on the demand for the ES (e.g. the number of floods informs us about the need for flood prevention, but does not in itself elucidate the ES Water Regulation). Another abstract measure is one where the resources used to obtain the benefit are measured and expressed as productivity (e.g. the volume of water or energy needed to produce a kg of crops). In the case of cultural ES, measures can, for example, be based on manmade facilities needed for recreation, symbolic or spiritual activities.

Rethinking the ES cascade

As the number of papers dealing with ES is booming, so too is the confusion and lack of consensus about how to measure and quantify ES. We argue that this is due to the overlap and the lack of clarity on definitions of parts of the ES cascade. When following the accepted definitions, no measures emerged specifically quantifying the ES part of the cascade. Rather, measures are linked to quantification of the functioning of the ecosystem (ecological side of the cascade), or to the quantification of the benefits (socio-economic side). A typical regulating ES example is carbon sequestration (kg year $^{-1}$ or kg m^{-2} year $^{-1}$), which gives an indication of the functioning of the ecosystem in relation to the ES Climate Regulation. This is a commonly accepted measure for the ES but it is purely indicative of the capacity of the ecosystem to supply the ES without considering the benefits to society (socio-economic side of the cascade, e.g. health improvements, or safety from extreme events linked to climate change). A typical example of the provisioning ES Food Production is fish landings (kg, or number of fish), which gives an indication of the total amount used by society, but not of the sustainable capacity of the ecosystem to deliver the ES (ecological side of the cascade). This demonstrates that the link between ecosystems and human well-being is currently not being well made.

We present a revised ES cascade which emphasizes the point that one measure for an ES is insufficient – at least two measures are needed, one for the ecosystem function (supply of ES) and another for the benefit to humans (demand of ES) (Fig. 4). This is why we present ES in the cascade not as a fifth block or 'measurable entity' in the centre called 'ES', but rather as a concept (represented by a dotted line) that encompasses both the supply and demand of an ES as a whole. A similar conclusion was reached by Mononen *et al.* (2016) where they assigned indicators to four parts of the ES cascade, and they considered the ES to be the summation of these four parts. The aim of our cascade model is to provide clarity on which aspects are important for sustainable ES delivery and hence what can and should be measured for each ES. We believe that the solution to the confusion is not to produce more detailed and complex cascades, but to keep it simple and the definitions clear.

Recommendations

1. BRIDGING THE GAP BETWEEN ECOLOGICAL AND SOCIO-ECONOMIC ASPECTS

To quantify the sustainable supply of an ES, it is necessary to quantify the properties and functions of an ecosystem (ecological side of the cascade), whereas to quantify the importance to society it is necessary to understand and quantify the benefit to society (socio-economic side). Many researchers are only considering one side of this cascade and therefore are not succeeding in understanding the whole picture. Do all future studies need to quantify each side of the ES cascade? This will largely depend on the aim of each individual study (Martinez-Harms *et al.* 2015); however, we argue that researchers should be aware of and be explicit about which aspect of the cascade they are considering and recognize the limitations of quantifying only one side of the ES cascade.

2. RELATIONSHIPS BETWEEN ES

The fact that all 21 ES very clearly clustered either to the ecological or to socio-economic side of the cascade (Fig. 3) would suggest that the functioning of some ES underpins the delivery of other ES. Our analysis shows which ES are limited to measures of function and for these, benefits are mostly not considered. On the other hand, measures for other ES are limited to benefits and functions are not measured. One example is that the ES Soil Quality Regulation and Soil Retention underpin the delivery of *inter alia* Food Production, which is the tangible benefit to society. For a detailed account of this, Dominati *et al.* (2014) study the role of soil in ES delivery for agro-ecosystems. We expect that there is a large amount of specialized research on ecosystem functions underpinning ES for which measures of function are scarce, but this is not taking place within the field of ES. Therefore, there is a need for more integration between the field of ES and more specialized fields. If it is not possible to find measures of both function and benefit for an ES, then it is possible that it is not a true ES. We

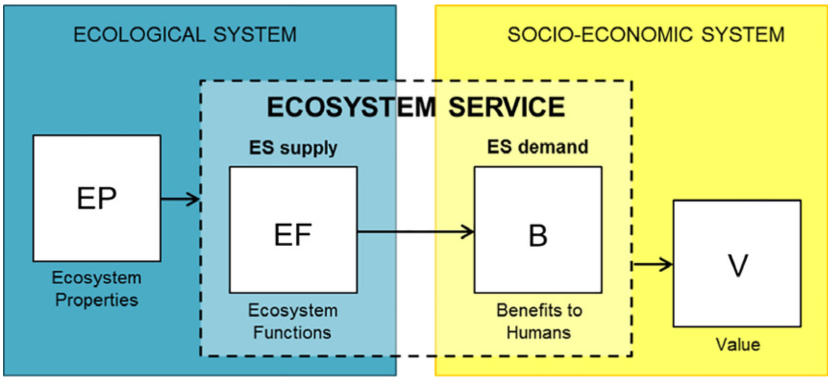

Fig. 4. Proposed conceptual framework for ecosystem services (ES) based on the ES cascade from Potschin & Haines-Young (2011). [Colour figure can be viewed at wileyonlinelibrary.com].

recommend more discussion on the relationships between ES to elucidate which ES are true ES and are essential to consider in ES assessments.

3. TIGHTER DEFINITIONS FOR ES

It is argued that the vagueness and imprecision in the definitions of ES and the ES concept as a whole encourages creativity and transdisciplinary collaboration (Schröter *et al.* 2014). While this is possible, there are many studies where this has led to confusion about what constitutes an ES, lack of transparency and inappropriate methods of quantification. For example, some studies split ES into subservices and report these as multiple, full ES which could give a false impression or result in double counting (e.g. Food Production split into eight different ES based on different fish species, Kozak *et al.* 2015). Some studies are not explicit about what constitutes an ES nor how they measure them (Niu *et al.* 2012), and there are also examples of parameters being included as ES which are clearly not ES, for example 'productivity' (Dobbs, Kendal & Nitschke 2014). Another example is that many researchers are using the exact same measure for all cultural ES, demonstrating that the differences between the cultural ES are not clear. On the other hand, different researchers use different measures for each cultural ES and this wide diversity could indicate a lack of consensus on what the ES actually is (similar to the findings of Luederitz *et al.* 2015). This definition confusion may lead to an overestimation of ES delivery, and ultimately double counting as well as problems with comparability. In spite of the argument that a final classification is perhaps neither possible nor necessary (Fisher, Turner & Morling 2009), given the multiple examples of confusion resulting from loose definitions, we call for some naming conventions, for example corporately accepting one of the ES classifications (e.g. TEEB or CICES) and a set of recognized measures. This would be possible to achieve without losing the flexibility which is necessary for the high diversity of studies applying the ES concept. While creativity is to be encouraged, transparency is essential. We recommend that ES papers should have a clear section in their methods stating exactly *which* ES they measured, and *how* they did this (for an example, see Perring *et al.* 2012 table 5).

4. COMPONENTS OF ES

All of the ES reviewed in our study are complex concepts made up of many different components although in many studies only one component is measured. The classic example is that of Climate Regulation, where carbon sequestration is often the only component measured although there are other essential components including, among others, climate moderation and sequestration of methane and nitrogen dioxide. Our results show a high diversity of measures for many ES (especially regulating ES), which could in part be explained by researchers variously measuring the many different components making up each ES. It is wrong to select just one of these components without evidence that this component is representative of the ES as a whole. Depending on the aim and scope of the study, there may be some cases where considering all components may not be relevant (e.g. a terrestrial study would not need to quantify fish landings for Food Production). The fundamental questions here are: 'What is necessary for an ES to be considered quantified?' 'Should all components be measured?' Either way, researchers should be clear about exactly which components are measured, and what is missing. We recommend further discussion on this topic and that some field-wide standards are chosen.

5. SELECTING GOOD-QUALITY ES MEASURES AND INDICATORS

Given that ES are so complex, having four different measureable parts from the cascade, each of which have different components that are difficult to measure, it would be impractical and probably impossible for every study to fully quantify each ES. Similar challenges of complexity in the field of ecology have resulted in the development of 'indicators' (Müller & Burkhard 2012). Indicators are not arbitrarily chosen proxies, but are carefully selected and tested to ensure that they adequately reflect the reality of the measure they are approximating, that they are scientifically rigorous and practically applicable (Kandziora, Burkhard & Müller 2013; after Müller & Burkhard 2012). Indicators have been proposed for ES and indeed even for each part of the ES cascade and different components within this (Layke *et al.* 2012; Kandziora, Burkhard & Müller 2013). However, the rigour of these indicators should be adequately assessed as some indicators are very weak. For example, from our analysis, it is clear that measures or indicators for ecosystem functions and benefits should be fluxes (based on rates with units g ha^{-1} year $^{-1}$ or m s^{-1}) and not stocks alone (g or ha or g ha^{-1}) (Appendix S1). We call for indicators to be proposed, developed and tested in the central parts of the ES cascade (functions and benefits, Fig. 4) either for each component, or an indicator that is demonstrated to be representative of all components within the ES (based on relationships). One suggestion is that collaboration should be increased between ES scientists and researchers from specialized fields within each ES to ensure adequate knowledge transfer. For example, there is much knowledge and there are many measures and techniques within the field of hydrology, which could be applied to estimate the biophysical aspect of the ecosystem service 'Water Regulation'.

6. SCIENTIFIC RIGOUR IN ES SCIENCE

Finally, there is a need to improve the overall scientific rigour of ES studies. More effort needs to be made by journals and reviewers to perform quality control: to ensure that methods are reported transparently (de Groot *et al.* 2012), that validation is done where appropriate and that some effort is made to estimate uncertainty. In general, there appears to be a large need for field validation of studies. In addition, when economic valuation is done, it is advisable that several methods are used to give a range of results, where the most conservative estimate should be chosen.

Conclusion

It is likely that researchers will never succeed in perfectly measuring the biophysical and socio-economic reality of all ES and hence will forever rely on indicators. ES research is looking for simple tools to translate biophysical and socio-economic studies into something useful for policy, and our review provides an overview of current gaps and six recommendations of how to improve the current measures to achieve a more realistic quantification of the reality.

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Data accessibility

Tables of ecosystem service measures are available as online supporting information.

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Appendix S1. Ecosystem service measures tables.